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DOI: https://doi.org/10.1055/s-0039-1678734



Originally published at:
Keller, Sara A; Valet, Sebastian; Martens, Ann; Weisse, Bernhard; Fürst, Anton E; Kümmerle, Jan M (2019). Problem of pin breakage in equine transfixation pin casting: biomechanical ex vivo testing of four different pins. Veterinary and Comparative Orthopaedics and Traumatology, 32(03):222-233.
DOI: https://doi.org/10.1055/s-0039-1678734

Published online: 07.03.2019



# Problem of Pin Breakage in Equine Transfixation Pin Casting: Biomechanical *Ex Vivo* Testing of Four Different Pins

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Vet Comp Orthop Traumatol 2019;32:222–233.

## Abstract

**Objective** The aim of this study was to evaluate cyclic fatigue behaviour of a new pin with a thread run-out design in comparison with three other types of pins commonly used for equine transfixation pin casting.

**Materials and Methods** Twenty-four pairs of equine cadaveric third metacarpal bones (MC3) equipped with one transfixation pin placed horizontally in the distal metaphysis were tested using a simplified model, mimicking the biomechanical situation of equine transfixation pin casting. A 6.3/8.0-mm Imex Duraface pin with thread run-out design (ITROP) was compared with a 6.1-mm smooth Steinmann pin (SSP), a Securos 6.2-mm, positive-profile pin (SPPP) and an Imex 6.3-mm, positive-profile pin (IPPP) under cyclic loading until failure in axial compression of MC3.

**Results** All pins broke at clinically relevant load levels and cycle numbers. The SSP endured significantly ($p = 0.0025$) more cycles before failure (mean: 48685) than the ITROP (mean 25889). No significant differences in cycles to failure were observed comparing the SPPP versus ITROP, and the IPPP versus ITROP, respectively.

**Clinical Significance** A thread run-out design does not necessarily lead to higher resistance against pin breakage under cyclic loading conditions. The SSP was most resistant against cyclic failure in these testing conditions, even though it was associated with more lateromedial displacement and cortical wear-out. This could outweigh reported disadvantages of the SSP such as reduced resistance to axial extraction and pin loosening.

**Keywords**

- horse
- transfixation
- pin
- breakage
- cyclic loading



## Introduction

Transfixation pin casting is a well-established treatment method for comminuted phalangeal fractures in equids and bovines.[1–3] It is recommended to place two to three pins horizontally in the metaphysis or distal diaphysis of the third metacarpal (MC3) or third metatarsal bone each diverging 10 to 15° from the dorsal plane, so that the pins diverge from each other by 30°.[1,3,4] The pin ends are then incorporated into a fibreglass cast. This allows the transfer of the axial weight bearing forces through the pins into the cast.[1,3,5,6] It was shown that, compared with a traditional short or full-limb cast, transfixation pin casting significantly reduces the bone strain in the proximal phalanx, as well as the displacement on a 30° osteotomy site in MC3.[7–10] The complications that may be associated with transfixation pin casting are pin tract infections, sequestrum formation, premature pin loosening, catastrophic fractures through the pin hole and pin breakage.[1,5,6]

**received** June 26, 2018
**accepted after revision** January 8, 2019



**DOI** https://doi.org/10.1055/s-0039-1678734.
**ISSN** 0932-0814.

Because of their higher resistance against extraction forces and pin loosening, positive-profile pins are preferred over smooth pins.[11–15] However, the junction between the threaded and smooth part of the pin is considered a weak spot prone to pin breakage. To overcome this problem, new pins with a tapered thread run-out design were developed. These thread run-out pins have an increased shaft diameter and a more continuous transition from the threaded to the non-threaded part of the pin. Pins with the thread run-out design were evaluated in a biomechanical testing apparatus designed to mimic use of the pins for external fixation in small animals.[16] It was shown that the thread run-out system had an increased stiffness and increased resistance to cyclic fatigue compared with positive-profile threaded half-pins for use in small animal surgery.[16] For horses, pins with a thread run-out design have become available recently as well. Although pin breakage is a clinically relevant problem in equine transfixation casting,[17,18] no studies are available that compare the resistance of currently available pins against breakage under cyclic loading conditions.

The aim of this study was to compare currently available and relevant pins for equine transfixation pin casting in terms of their resistance to breakage under cyclic loading conditions.

Our hypothesis was that the newly designed 6.3/8.0 mm tapered thread run-out design pin is more resistant to cyclic failure than commercially available smooth and positive-profile pins.

## Materials and Methods

### Biomechanical Pilot Study

In a biomechanical pilot study, the applicability of a simplified test model without casting material was compared with a fibreglass cast model.

A 6.1 mm smooth Steinmann pin (SSP) (Synthes; West Chester, Pennsylvania, United States) was inserted into the distal metaphysis of each of a pair of equine cadaveric MC3. For the preparation of a fibreglass cast model in one limb of the tested pair of bones, two layers of padding material and an elastic bandage were used to create a padding layer with a thickness of approximately 2 cm followed by application of four rolls of 12.7 cm fibreglass cast (3M; Rüschlikon, Switzerland) to create a half-limb transfixation cast[1] (►**Fig. 1A**). For the simplified test model, the pin ends of the contralateral limb were inserted into polyoxymethylene-copolymer (POM-C) sleeves with a width of 1 cm supporting the pin. The POM-C sleeves were tightened around the pin to prevent axial rotation of the pins during loading. The POM-C sleeves were secured in the inner stainless-steel sleeves. These stainless-steel sleeves were designed to adjust the distance between bone and POM-C insert, which was kept at 2 cm simulating the conditions of a transfixation cast (►**Fig. 1B**).

In case of the fibreglass cast model, the load was applied to the proximal end of MC3 and transferred into the cast through the pin inserted through the distal part of this bone. The load applied to the cast was then transferred to the bottom plate of the set-up through a polymethyl methacrylate resin embedding. In case of the simplified test model, the load transfer into the cast was simulated by the POM-C cylinders placed and locked inside of stainless-steel cylinders, which were mounted to vertical plates to transfer the load into the bottom plate of the set-up.

Young's modulus of the POM-C cylinders and stainless-steel components was 3,000 MPa and 210,000 MPa, respectively. All pins tested in this study were made of medical grade stainless steel as specified in ISO 5832–1.

Two runs of cyclic loading were performed consecutively on each limb of the bone pair. For run 1, the bones were previously

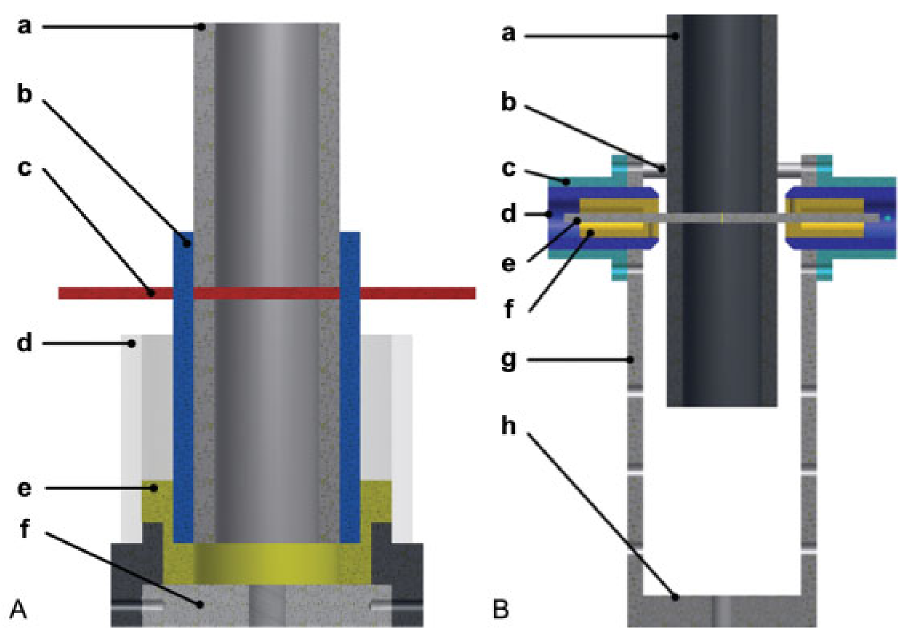


**Fig. 1** (**A**) Longitudinal section of the setup for the cast model: (**a**) Bone, (**b**) cast- and padding-material, (**c**) pin, (**d**) aluminium cylinder, (**e**) polymethyl methacrylate resin embedding, (**f**) ground plate. (**B**) Longitudinal section of the setup for the simplified test model: (**a**) Bone, (**b**) stainless steel rod, (**c**) outer stainless-steel sleeve, (**d**) inner stainless-steel sleeve, (**e**) pin, (**f**) polyoxymethylene-copolymer sleeve, (**g**) side walls, and (**h**) ground plate.

loaded five times from 100 N to 1000 N under axial compression resulting in a mixed compression/bending loading of the pin. The load was then increased by 500 N for each load level. Each load level was maintained for 50 cycles for a total of 200 cycles. The specimens were loaded with a frequency of 1 Hz. For run 2, the bones were previously loaded with the same increasing loads as in run 1. Then, the bones were loaded at the same load level at 3000 N for 400 cycles with a frequency of 1 Hz. For each run, the apparent stiffness (load/displacement of the test cylinder at the point of load introduction) at the beginning of the tests as well as the trend of the apparent stiffness under cyclic loading was recorded.

### Biomechanical Main Study

The 6.3/8.0 mm Imex Duraface thread-run-out design pin (ITROP) (Imex; Longview, Texas, United States) was compared with the SSP (test group 1), a Securos 6.2-mm, positive-profile pin (SPPP) (Securos Inc., Fiskdale, Massachusetts, United States) (test group 2) and an Imex 6.3 mm positive-profile pin (IPPP) (test group 3) under cyclic loading until failure in a configuration resulting in a mixed bending/compression loading of the pin achieved by axial loading of the MC3-pin construct. Load introduction was performed on the proximal aspect of MC3 in direction of the bone axis and perpendicular to the pin. In all three test groups comprising eight pairs of bones each, an ITROP was inserted in four randomly selected left and right MC3 respectively. The other pin (SSP, SPPP, or IPPP) was inserted in the corresponding contralateral bone of each pair of limbs (►**Fig. 2**).

### Preparation of the Bones and Pin Insertion

The 24 pairs of cadaveric forelimbs were harvested from adult horses euthanatized or slaughtered for reasons unrelated to this study and with no history of orthopaedic disease. The size of the horses ranged from that of adult Icelandic horses to Warmbloods. The bone at the level of pin insertion had a mean diameter of 54 mm. Limbs were kept at−20°C after harvesting until used. The limbs were then thawed at room temperature. Then, the metacarpi were dissected free from all soft tissues. To determine the exact site of pin location and to rule out any disorder of the bones, a dorsopalmar radiograph was taken of each bone using a direct radiography system (Fujifilm; Gierth HF400, high frequency diagnostic x-ray unit, Riesa, Germany) set at 80 kV and 10 mAs. A 20-gauge hypodermic needle was placed as a radiographic marker approximately 1 cm proximal to the epiphyseal scar. The intended medial entry and lateral exit points of the pin were marked. A 3.2-mm pilot hole was drilled in all specimens using an aiming device (DePuy Synthes Vet; West Chester, Pennsylvania, United States). Further drilling and tapping steps were as recommended by the manufacturer of the pins and recommendations in the literature.[1] For the IPPP and ITROP (►**Fig. 3A**), the 3.2-mm drill hole was enlarged sequentially by using a 4.5-mm drill bit, followed by a 5.5- and 6.2-mm drill bit. Tapping was then performed using the designated tap (Imex tap for 6.3 mm/8.0-mm Duraface full-pin for large animals, Imex, Longview, Texas, United States) before pin insertion.

For the SPPP (►**Fig. 3A**), the designated drill bit (Securos equine sequential drill bit; Securos Inc., Fiskdale, Massachusetts, United States) was used after creation of the initial 3.2 mm hole. This drill bit has a diameter of 4.5 mm at its tip and increases stepwise to 5.5 and 6.2 mm after every 20 mm length of the drill bit. Then, the SPPP was inserted.

For the SSP (►**Fig. 3A**), the 3.2-mm hole was first enlarged with a 4.5-mm drill bit, followed by a 5.5-mm and a 6.0-mm drill bit prior to pin insertion.

During all drilling procedures, water irrigation of the drill bit was performed.

One pin was then implanted transversely in the distal metaphysis of each MC3 in a medial to lateral direction so that the ends of the pins protruding from the medial and lateral cortex, respectively were of equal length (►**Fig. 3B**). The bone diameters were measured at the points where pins emerged from the bones. After pin-insertion, the bones were wrapped in moist cloths and frozen (−20°C) until used for biomechanical testing.

### Test Set-Up

Five markers (M1 to M5) were fixed on each bone (►**Fig. 4**) and the pins to allow monitoring of the pin position in relation to the bone with the help of a camera (ECO655 MVGE; Monochrome 2448 × 2050 Pixel, mounted with a f = 40 mm lens,

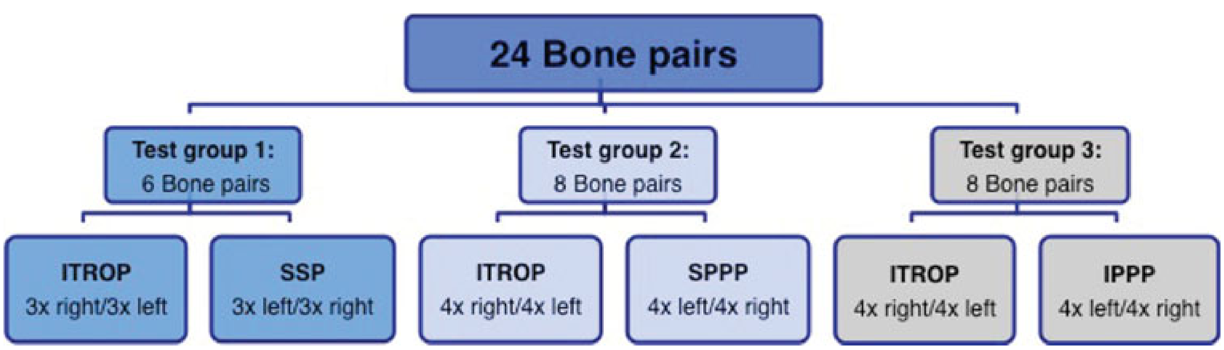


**Fig. 2** Illustration of the study design. The ITROP was inserted in four right and four left limbs of the bone pairs. The other pin type was inserted contralaterally. Two bone pairs of test group 1 had to be excluded from the study. Abbreviations: IPPP = Imex 6.3-mm centrally threaded positive profile pin; ITROP, Imex 6.3/8.0-mm Duraface pin with thread run-out design; SPPP, Securos 6.2 mm centrally threaded positive profile pin; SSP, 6.1-mm smooth Steinmann pin.

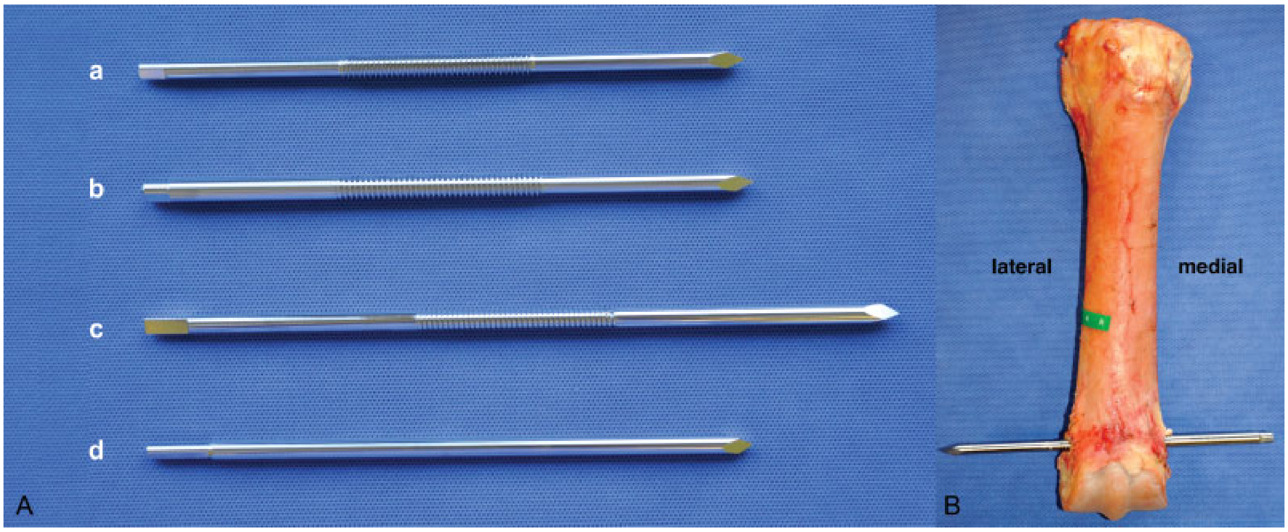


**Fig. 3** (**A**) The four different types of pins used in this study: (**a**) Imex 6.3-mm centrally threaded positive profile pin; (**b**) Imex 6.3/8.0-mm Duraface pin with thread run-out design; (**c**) Securos 6.2-mm centrally threaded positive profile pin; (**d**) A 6.1-mm smooth Steinmann pin. (**B**) Third metacarpal bone with a 6.3/8.0 mm Imex Duraface pin with thread run-out design inserted in the distal metaphysis.

SVS Vistek, Seefeld, Germany; analysis with Maxtron Image Design Assistant, Dorval, Canada). M1 and M2 were attached to the middle of the free length (= 2 cm) of the pin on the lateral and medial side respectively. The M3 and M4 were placed on the dorsal aspect of the bone close to where the pin emerged from the bone laterally and medially respectively. The M5 was used as a reference point in case of movement of the camera and was placed on the middle of the connecting rod of the lateral and medial plates. The camera recorded 30 consecutive images in 11.6 seconds every 5 minutes and registered the movement of the five markers in the X- and Y-direction.

The bone–pin constructs were mounted to the testing apparatus so that the distance between the bone surface and the POM-C sleeve was adjusted to 2 cm. Proximally, the bones were fastened with a fixture that was attached to the load cell of the testing machine (20 kN hydraulic cylinder with Instron IST control unit 8800; Norwood, Massachusetts, United States) (►**Fig. 4**).

## Biomechanical Testing

Load was applied in a loading configuration simulating the clinical conditions that exposed the pin to a mixed bending/compression loading. The constructs were preloaded with 100 N. Then, the first load level of 2000 N was applied. Every load level was maintained for 10,000 cycles with a load-controlled sinusoidal oscillation of 2 Hz, followed by an increase of 500 N for each of the following load levels (►**Table 1**). All load steps throughout the testing were performed automatically with a test loading programme without an interruption between the load steps. The transition between the cyclic loading steps was done with a linear load-controlled ramp. The load cycles were faded in within 3 seconds. The specimens were all tested until failure. The failure criterion was defined as complete loss of stability, as it occurs in case of complete pin breakage. This was detected by the machine once the lower load could not be maintained due to loss of stability.

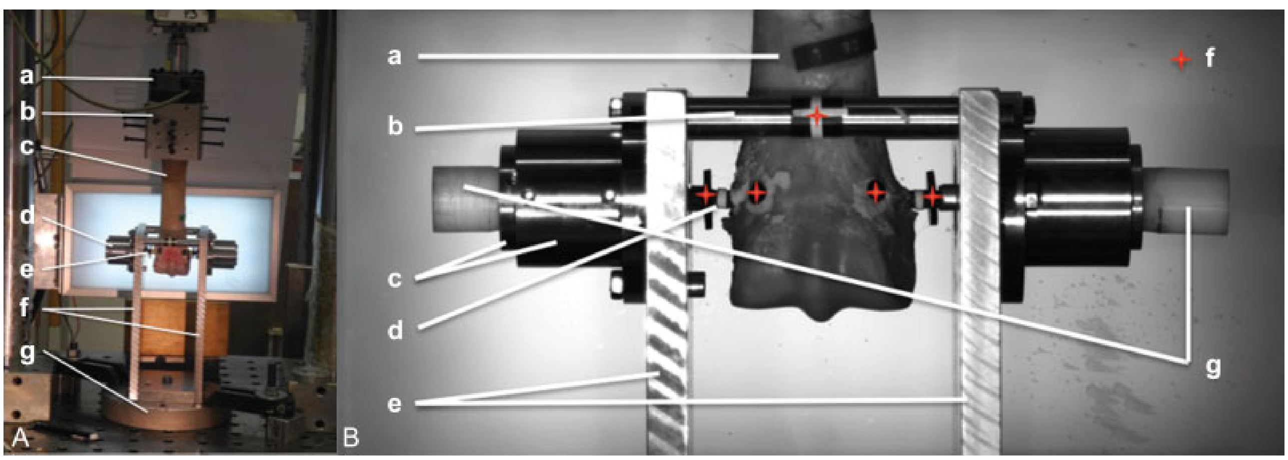


**Fig. 4** (**A**) Overview of the test setup: (**a**) Load cell, (**b**) fixation profile, (**c**) bone, (**d**) outer stainless-steel sleeve, (**e**) pin, (**f**) vertical side plates, (**g**) ground plate. (**B**) Close-up view of the test setup: (a) Bone, (**b**) stainless steel rod, (**c**) inner and outer stainless-steel sleeves, (**d**) pin, (**e**) vertical side plates, (**f**) markers, (**g**) round profiles.

**Table 1** Load protocol of the biomechanical main study

| Step | No. of cycles | Total cycles | Load/ upper load | Lower load | Amplitude | Middle | Load rate/ frequency |
|---|---|---|---|---|---|---|---|
| – | – | | *N* | *N* | *N* | *N* | |
| 0 Preload | – | – | Quasistatic 100 N | | | | X N/s |
| 1a Static | | | 1,050 (middle load of 1b) | | | | |
| 1b Cyclic | 10,000 | 10,000 | 2,000 | 100 | 950 | 1050 | 2 Hz |
| 2a Static | | | 1,300 (middle load of 2b) | | | | X N/s |
| 2b Cyclic | 10,000 | 20,000 | 2,500 | 100 | 1200 | 1300 | 2 Hz |
| 3a Static | | | 1,550 (middle load of 3b) | | | | X N/s |
| 3b Cyclic | 10’000 | 30,000 | 3,000 | 100 | 1450 | 1550 | 2 Hz |
| 4a Static | | | 1,800 (middle load of 4b) | | | | X N/s |
| 4b Cyclic | 10,000 | 40,000 | 3,500 | 100 | 1700 | 1800 | 2 Hz |
| 5a Static | | | 2,050 (middle load of 5b) | | | | X N/s |
| 5b Cyclic | 10,000 | 50,000 | 4,000 | 100 | 1950 | 2050 | 2 Hz |
| 6a Static | | | 2,300 (middle load of 6b) | | | | X N/s |
| 6b Cyclic | 10,000 | 60,000 | 4,500 | 100 | 2200 | 2300 | 2 Hz |
| 7a Static | | | 2,550 (middle load of 7b) | | | | X N/s |
| 7b Cyclic | 10,000 | 70,000 | 5,000 | 100 | 2450 | 2550 | 2 Hz |

An additional alternative failure criterion was defined by a reduction in the apparent stiffness by 35% with respect to the initial stiffness at test start.

Every 20 cycles, one full cycle of the sinusoidal loading was recorded and the corresponding statistical values were calculated including minimum and maximum values, root mean square and amplitude of the load signal as well as of the displacement signal. The interval of 20 cycles was determined in a pre-test and found to allow an appropriate time resolution to identify changes throughout the test.

The location of primary pin breakage was identified using iteratively recorded images throughout the test and categorized into three groups: (a) initial breakage on medial side, (b) initial breakage on lateral side or (c) breakage on both the medial and lateral side where the side of primary breakage could not be fully resolved.

Following biomechanical testing, each specimen was examined macroscopically and radiographically to evaluate the location of pin breakage, screen for bone fractures and document whether there was obvious wearing out of the cortices.

### Statistical Analysis

A statistical software package (SPSS, IBM, version 24) was used to evaluate normal distribution of cycles to failure with the Kolmogorov-Smirnov test and to compare groups using a paired *t*-test with $p$ set at $<0.05$. The likelihood of cortical wear-out around the pins was compared by calculating the odds ratio and their 95% confidence interval (CI). Additionally, the correlation between lateromedial bone diameter at the level of the pins and the number of cycles endured before failure of all bones equipped with ITROP was investigated using the Pearson correlation coefficient.

## Results

### Biomechanical Pilot Study

The apparent stiffness of the simplified test model was 6.7% higher than the apparent stiffness of the cast model after the first 50 cycles in run 1 with a load of 1000 N. With increasing cycle numbers, the apparent stiffness of the cast model decreased by 18.9% after 200 cycles of run 1 and by 32.7% after 600 cycles of run 2 respectively, compared with the starting point. Conversely, the stiffness of the simplified test model showed an increase of 5.8% after 600 cycles of run 2. Load-displacement plots of a few load cycles at the end of each load level illustrate the apparent stiffness of the construct as well as a displacement drift of the position at middle load (between upper and lower load value) (►**Fig. 5**).

### Biomechanical Main Study

Because of marked lateromedial pin displacement in the first two experiments, the first two bone pairs (equipped with SSP and ITROP respectively) had to be excluded from the study. Two round profiles were then plugged into the inner stainless-steel sleeve in the consecutive experiments to limit lateromedial displacement of the pins. All specimens failed by pin breakage. The localization of primary pin breakage sites is shown in ►**Table 2**.

The SSP endured a mean of 48,685 cycles (standard deviation [SD] = 7,869) and failed at load levels between 4,000 and 5,000 N. The SPPP endured a mean of 29,276 cycles (SD = 7390) and failed at load levels between 2,500 and 4,000 N. The IPPP endured a mean of 41,179 cycles (SD = 6,648) and failed at load levels between 3,500 and 4,500 N. The ITROP endured a mean of 31,061 cycles ($n = 22$:

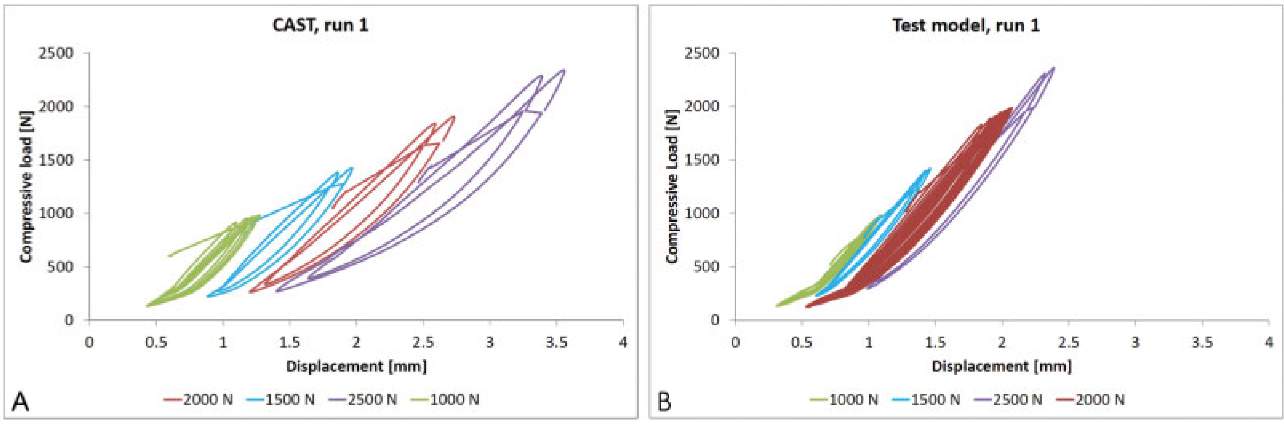


**Fig. 5** Comparison of mechanical behaviour of the fibreglass cast model (**A**) and the simplified test model (**B**) with a 6.1-mm smooth Steinmann pin used in each. Load-displacement plots at different load-levels are shown. The slope corresponds to the apparent stiffness of the model.

**Table 2** Location of primary pin failure during cyclic testing

| Group | Medial | Lateral | Medial + Lateral |
|---|---|---|---|
| ITROP of group 1 ($n = 6$) | 4x | 1x | 1x |
| SSP of group 1 ($n = 6$) | 3x | – | 3x |
| ITROP of group 2 ($n = 8$) | 6x | 1x | 1x |
| SPPP of group 2 ($n = 8$) | 3x | 4x | 1x |
| ITROP of group 3 ($n = 8$) | 4x | 1x | 3x |
| IPPP of group 4 ($n = 8$) | 7x | – | 1x |

Abbreviations: IPPP, Imex 6.3-mm centrally threaded positive profile pin; ITROP, Imex 6.3/8.0 mm Duraface pin with thread run-out design; SPPP, Securos 6.2-mm centrally threaded positive profile pin; SSP, 6.1-mm smooth Steinmann pin.

SD = 6,910) overall and failed at load levels between 3,000 and 4,000 N. Specifically, the ITROP endured a mean of 25,889 cycles (SD = 2,661) in test group 1 (ITROP vs. the SSP), a mean of 27,689 (SD = 4,008) in test group 2 (ITROP vs. the SPPP) and a mean of 38,313 (SD = 5′108) in test group 3 (ITROP vs. the IPPP) (►**Fig. 6** and ►**Table 3**).

The data obtained for the endured cycle numbers were normally distributed. The number of cycles before pin failure was significantly higher for the SSP compared with the ITROP ($p = 0.0025$). No significant differences in endured cycle numbers were found between ITROP and SPPP ($p = 0.626$) and between ITROP and IPPP ($p = 0.244$) (►**Fig. 6**).

The initial stiffness of SSP was significantly lower than for ITROP, whereas no significant differences could be observed in the other test groups (►**Fig. 7**). A reduction in the apparent stiffness indicated an early stage of failure due to plastic deformation and/or cracking. The condition of 35% reduction in apparent stiffness occurred in all cases before the primary breakage occurred. Mean number of cycles sustained before the 35% reduction in apparent stiffness occurred was significantly higher for SSP compared with ITROP ($p < 0.01$) but there were no significant differences in the other test groups (►**Fig. 8**).

Wearing out of the cortices around the pin was noted in 5 out of 6 SSP, 7 out of 8 SPPP, 5 out of 8 IPPP and 7 out of 22 ITROP specimens (►**Fig. 9**). The odds ratio for the appearance of wearing out of the cortices was 2.619 (95% CI: 1.29–5.32) when SSP were compared with ITROP, 2.75 (95% CI: 1.41–5.35) when SPPP were compared with ITROP and 1.96 (95% CI: 0.87–4.43) when IPPP were compared with ITROP.

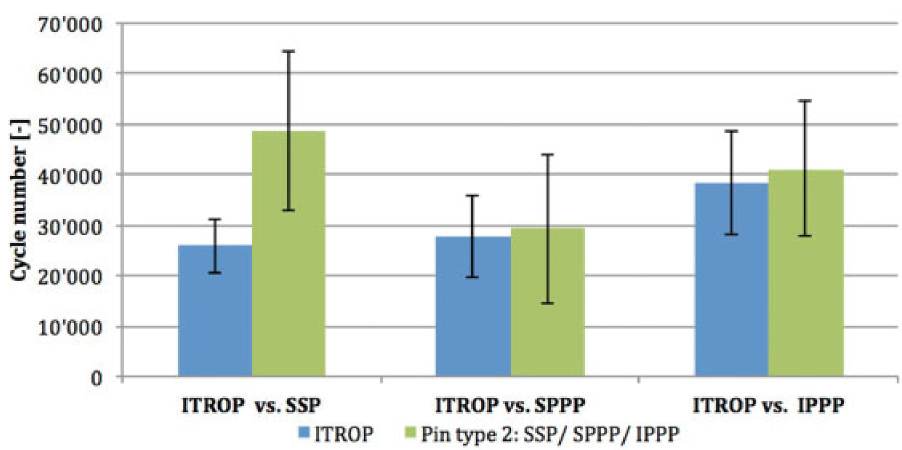


**Fig. 6** Means of endured total cycle numbers of the different pin types before failure. Error bars ± 2 x SD. Abbreviations: IPPP, Imex 6.3-mm centrally threaded positive profile pin; ITROP, Imex 6.3/8.0-mm Duraface pin with thread run-out design; SD, standard deviation; SPPP, Securos 6.2-mm centrally threaded positive profile pin; SSP, 6.1-mm smooth Steinmann pin.

**Table 3** Number of cycles endured before failure and load levels at failure

| Group | Mean of cycles endured before failure | Standard deviation of cycles endured before failure | Load levels at failure |
|---|---|---|---|
| ITROP of group 1 | 25,889 | 2,661 | |
| SSP of group 1 | 48,685 | 7,869 | 4,000–5,000 N |
| ITROP of group 2 | 27,689 | 4,008 | |
| SPPP of group 2 | 29,276 | 7,390 | 2,500–4,000 N |
| ITROP of group 3 | 38,313 | 5,108 | |
| IPPP of group 3 | 41,179 | 6,648 | 3,500–4,500 N |
| ITROP over all groups | 31,061 | 6,910 | 3,000–4,000 N |

Abbreviations: IPPP, Imex 6.3-mm centrally threaded positive profile pin; ITROP, Imex 6.3/8.0-mm Duraface pin with thread run-out design; SPPP, Securos 6.2-mm centrally threaded positive profile pin; SSP, 6.1-mm smooth Steinmann pin.

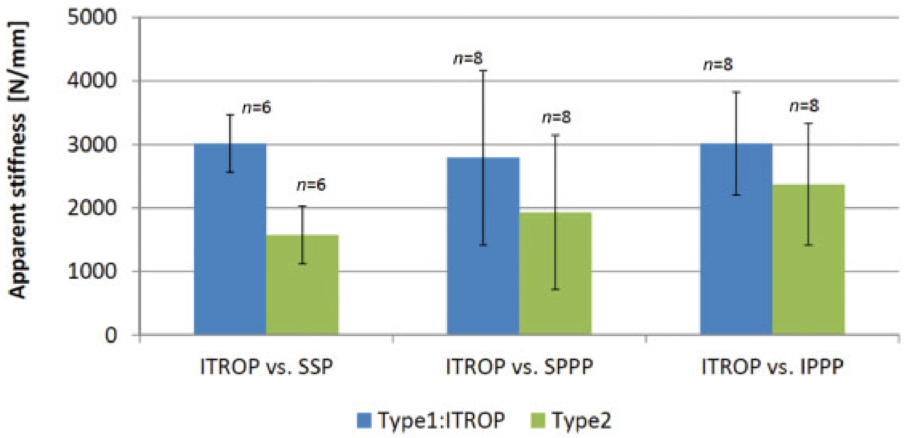


**Fig. 7** Initial apparent stiffness of different test groups illustrating a significantly higher stiffness of the ITROP compared with the SSP. Error bars ± 2 x SD. IPPP, Imex 6.3-mm centrally threaded positive profile pin; ITROP, Imex 6.3/8.0-mm Duraface pin with thread run-out design; SD, standard deviation; SPPP, Securos 6.2-mm centrally threaded positive profile pin; SSP, 6.1-mm smooth Steinmann pin.

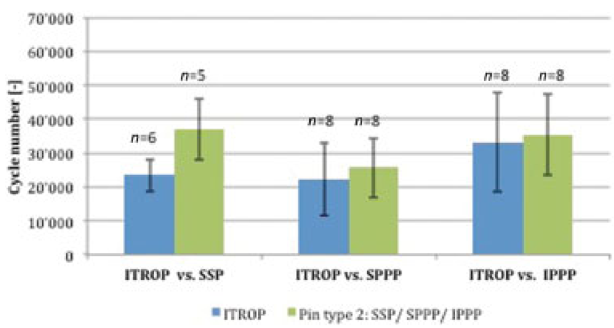


**Fig. 8** Means of endured total cycle numbers of the different pins at 35% stiffness reduction. Error bars ± 2 x SD. IPPP, Imex 6.3-mm centrally threaded positive profile pin; ITROP, Imex 6.3/8.0-mm Duraface pin with thread run-out design; SD, standard deviation; SPPP, Securos 6.2-mm centrally threaded positive profile pin; SSP, 6.1-mm smooth Steinmann pin.

Therefore, cortical wear-out was significantly more likely when SSP or SPPP were used compared with ITROP.

Lateromedial displacement of the pin in relation to the bone during cyclic loading was most pronounced in specimens with the SSP.

The mean of the lateromedial bone diameters of the bones at the level of the pins was 57.0 mm (95% CI: 51.7–62.3) for test group 1 (ITROP vs. SSP), compared with 52.2 mm (95% CI: 48.8–55.5) for test group 2 (SPPP vs. ITROP) and 52.7 mm (95% CI: 49–56.3) for test group 3 (IPPP vs. ITROP). There were no significant differences in bone diameter between the test groups. There was also no significant correlation between bone diameter and the endured number of cycles before failure ($p = 0.5$).

After biomechanical testing, pin breakage on both the medial and lateral aspect was observed in 39 of the 44 pins. Two pins (1x ITROP, 1x SSP) broke only at the medial aspect and showed pin bending at the lateral aspect. In two pins (1x ITROP, 1x SSP), pin breakage occurred at the medial aspect, but there was no sign of pin failure on the lateral aspect. Finally, one pin (1x SPPP) showed pin breakage at the lateral aspect and only pin bending at the medial aspect. There was no significant difference in the frequency of medial versus lateral pin failure in cases of unicortical pin failures ($p = 0.11$).

The SSP broke twice at the bone surface and five times at the inner surface of the cortex. Bending without breakage occurred at one location in a single SSP. In two SSP specimens, the pin fell out of the bone so that the exact location of pin breakage could not be evaluated. In the SPPP, pin breakage occurred four times at the bone surface, six times within the cortex and three times at the inner surface of the cortex.

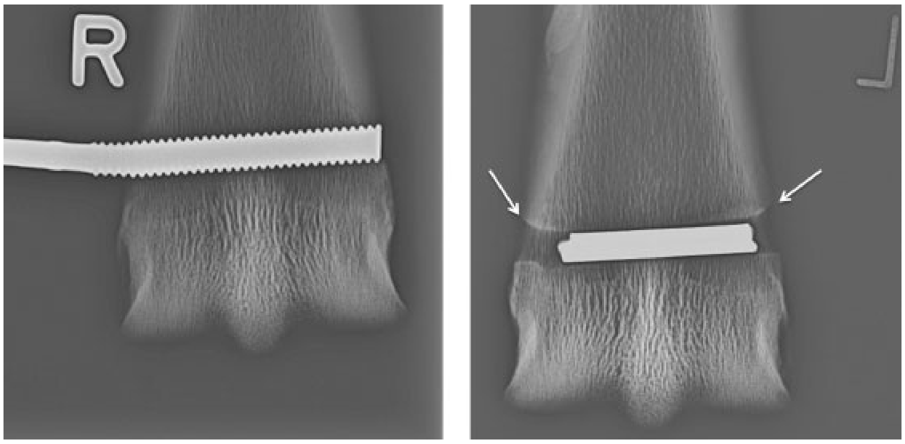


**Fig. 9** Radiographs of bone pair no. 6 taken after biomechanical testing. The right bone (labelled with an 'R') had been equipped with an ITROP (Imex 6.3/8.0-mm Duraface pin with thread run-out design), the left bone (labelled with an 'L') with an SSP (6.1-mm smooth Steinmann pin). In these specimens, pin breakage occurred unicortically at the medial bone surface in the bone equipped with an ITROP and bilaterally at the inner surface of the cortex in the bone with a SPP. Cortical wear-out (white arrows) is evident around the pin hole in the bone with an SSP but not in the bone with an ITROP.

Bending without breakage was observed at one location in a single SPPP specimen. In one SPPP, the exact location of pin failure could not be evaluated because of marked lateromedial displacement of the pin. The IPPP broke seven times at the bone surface, seven times within the cortex and twice at the inner surface of the cortex. In the ITROP, the pin breakage occurred 29 times at the bone surface, 12 times at the cortex and once at the inner surface of the cortex. Bending without breakage was observed at one location in only one ITROP specimen. In the threaded pins (SPPP, IPPP and ITROP), pin breakage always occurred in the threaded parts of the pins. In total, pin breakage occurred 42 times at the bone surface, 25 times within the cortex and 11 times at the inner surface of the cortex.

Fracturing of the bone was observed once in a bone equipped with an SSP that sustained an incomplete fracture of the lateral cortex.

## Discussion

This study showed that pins commonly used for equine transfixation pin casting undergo cyclic failure at clinically relevant load levels and cycle numbers. Furthermore, it revealed that a thread run-out design does not necessarily lead to improved resistance against cyclic fatigue.

In the pilot study, it was shown that the simplified model represented a condition which critically simulated cyclic pin bending in transfixation constructs with fibreglass casts. Bending occurring close to the bone cortex is a mix between 3-point bending and a cantilever bending. The outer side of the pin which is retained by the cast/POM-C cylinder simulating the cast is hindered from freely rotating but can still rotate somewhat. If the outer ends of the pin could freely rotate, it would be close to a cantilever bending causing increased bending stresses close to the bone. Once the pin is hindered from rotating at this location, it induces an additional bending moment and thus stress, which is dependent on the stiffness retaining/hindering the rotation and thus inducing bending stress. We suggest that the accelerated reduction in apparent stiffness in the cast model compared with the simplified test model could be explained by wearing out at the pin–cast interface and higher extent of deformation of the cast material compared with the POM-C sleeves. Conversely, the apparent stiffness of the simplified test model even slightly increased with cycle numbers. This change of apparent stiffness is suggested to be attributed to plastic deformation of the pin and a settling of different components of the test set-up including deformation of cast material and clearance of test adapters. The apparent stiffness depends on several factors such as stiffness of single components (e.g. pin, cast and bone) and the interaction between them. An increase in stiffness can be due to the fact that any clearance in the system arising from its different components is lowered or even eliminated during repeated loading. Comparing the initial loading behaviour of the pin in the cast versus the simplified test model, the pins were expected to be exposed to higher stress concentrations in the simplified model because of a less compliant system at the sites of pin incorporation in the sleeves. Furthermore, use of a simplified model reduces the number of potential confounding variables such as the quality of the cast and inevitable differences between individual cast constructs.

Forces in MC3 in horses with a bodyweight of 450 to 550 kg are between 2753 N when standing and 7517 N at the walk.[19] Healthy horses confined to a box in a new environment make a mean of 4560 steps in 24 hours.[20] These values of forces and step numbers compare favourably with the failure loads of 2,500 to 5,000 N and endured cycle numbers between 29,276 and 48,685 in our biomechanical testing, confirming its clinical relevance. In the clinical situation, the forces that act on the implants during recovery from general anaesthesia represent an additional peak loading situation for the bone–implant construct. Another clinical consideration is that a transfixation pin cast is usually left in place for approximately 6 weeks[6] which—using the numbers mentioned above—would correspond to 19,1520 cycles of loading with a force of 7,517 N. Vice versa, the mean number of cycles endured before failure of the pin that performed best in our study, that is, the SSP, corresponds to the number of cycles that a horse confined to a box makes in 10 to 11 days. However, several other factors should be considered clinically, for example, less movement of a horse that suffers from a painful condition compared with a healthy horse, load distribution between implants when two or more implants are used in a transfixation pin cast construct, the influence of using cast material compared with our simplified model and the huge effect of muscular contractions on local stress distribution in bone.[21]

For the biomechanical testing, cyclic loading with a staircase load increase was used. This testing method is thought to have the advantage of being less sensitive to different influencing factors compared with the cyclic loading on one load level. Influencing factors beside the pin type are bone size and density, conditions and quality of repair insertion, differences in load distribution for different pin designs and materials. For example, a fixed load value may induce failure in one tested bone pair, whereas in another bone pair it may not cause failure due to a more stable repair which would make it more difficult to compare the pin design to each other. The choice of this method allowed inducing pin failures at clinically relevant load levels and the comparison of different pin types with an appropriate number of cycles.

In the simplified testing model used in this study to mimic the biomechanical environment of pins in equine transfixation pin casting, the SSP showed the highest resistance to failure under cyclic loading.

A possible explanation for the superior results achieved with the SSP is the fact that threaded pins are more resistant to extraction forces, but have more stress-concentrating points. The thread run-out design of the ITROP tries to overcome the problem of stress concentrating points with a steadily increasing shaft diameter and decreasing height of the thread profile. In a biomechanical study relevant for external fixation in small animals, the thread run-out design proved to be associated with significantly higher resistance to cyclic failure.[16] However, several variables in this study were different from our approach and this could explain the different results, for example, pins were not implanted in cadaveric bone, but into a solid acetyl cylinder, the ITROP was inserted with the thread run-out section at the level of the surface of the acetyl cylinder, the bending moment arm was larger and the loading protocol was different.

However, this could not be confirmed in our testing model relevant for equine transfixation pin casting. It is known that smooth pins loosen faster than threaded pins under cyclic loading.[12,14] We observed that marked lateromedial displacement of the pin in relation to the bone occurred in our testing model initially and this led to exclusion of the first two pairs of bones in testing group 1. After this experience, we fixed the ends of the pins in our testing apparatus for all subsequent tests. This is similar to the situation in a real transfixation cast where the ends of the pins are fixed laterally and medially in the cast material as well. Despite this, we still observed more lateromedial movement of the pins in relation to the bone with the SSP compared with the other pin types. We suggest that the remarkably higher lateromedial displacement of the SSP (►**Fig. 10**) had a positive effect on the breaking strengths of the pins. As the pin gets loose and begins to move lateromedially in relation to the bone, it is not always stressed at the same two points where the pin emerges from the bone. This leads to a less critical testing of the pin and a higher breaking strength.

The most common failure mode was medial and lateral pin breakage. Failure was most commonly initiated by primary pin breakage medially. Pins usually broke at the inner or outer surface of the MC3 cortices. The metacarpal cortices correspond to the loading points in the bending configuration where the region near the bony surfaces acts as stress-concentrating points. For threaded pins, the site of breakage was within the threaded part of the pins. This may be explained by the fact that the length of the centrally threaded part of the pins exceeded the width of the MC3 bones at the site of pin insertion. Therefore, it was always the threaded part of the pins that was located at the stress-concentrating points at the bony cortices. This might be another reason why the potentially superior thread run-out design of the ITROP pins was not associated with increased biomechanical endurance of these pins, that is, the improved junction between the threaded and non-threaded part of the pin was not located at the critical bone–pin interface because the length of the threaded part of this pin did not correspond to the width of the bone at the site of pin insertion.

None of the pins showed considerable plastic deformation of the pin in the region close to the primary breakage. All pins which developed sequential breakage (i.e. the pin first broke at the site of primary breakage—mostly medially—and then another pin breakage occurred at the opposite cortex) exhibited a plastic deformation at the aspect opposite to the site of primary breakage. All pins were made of stainless steel. The yield strength of the steel used in the pins was not determined. Typical values of the yield strength of medical stainless steel used for implants are between 700 and 800 MPa[22] and ISO 5832–1 specifies a range of 860 to 1100 MPa for the ultimate strength. The pin region at the cortex opposite to the cortex associated with the primary breakage exhibited a stronger degree of plastic deformation. This can be by the fact that after the primary breakage had occurred, the opposite pin–bone interface had to carry all of the applied load which caused the bending stresses to exceed the yield of the material. Therefore, it was assumed that bending stresses on the side with the primary breakage did not considerably exceed the yield strength. Inspection of the break area at the site of primary breakage typically revealed a crack growth initiated from the bottom tensile stress side close to the cortex in the region of highest bending stress and leading to a fast breakage once the remaining cross-sectional area could not withstand the loading anymore.

Cortical wear-out occurred significantly more often in SSP and SPPP constructs compared with ITROP. Cortical wear-out is associated with pin loosening and bone weakening as the bone defect is increased and may, therefore, promote catastrophic failure through the pinhole. The wear-out also leads to a prolonged effective lever arm. As the bending moment is the product of the lever arm times the applied force,[12] the prolonged lever arm results in an increased bending moment of the pin and, therefore, these pins were expected to be

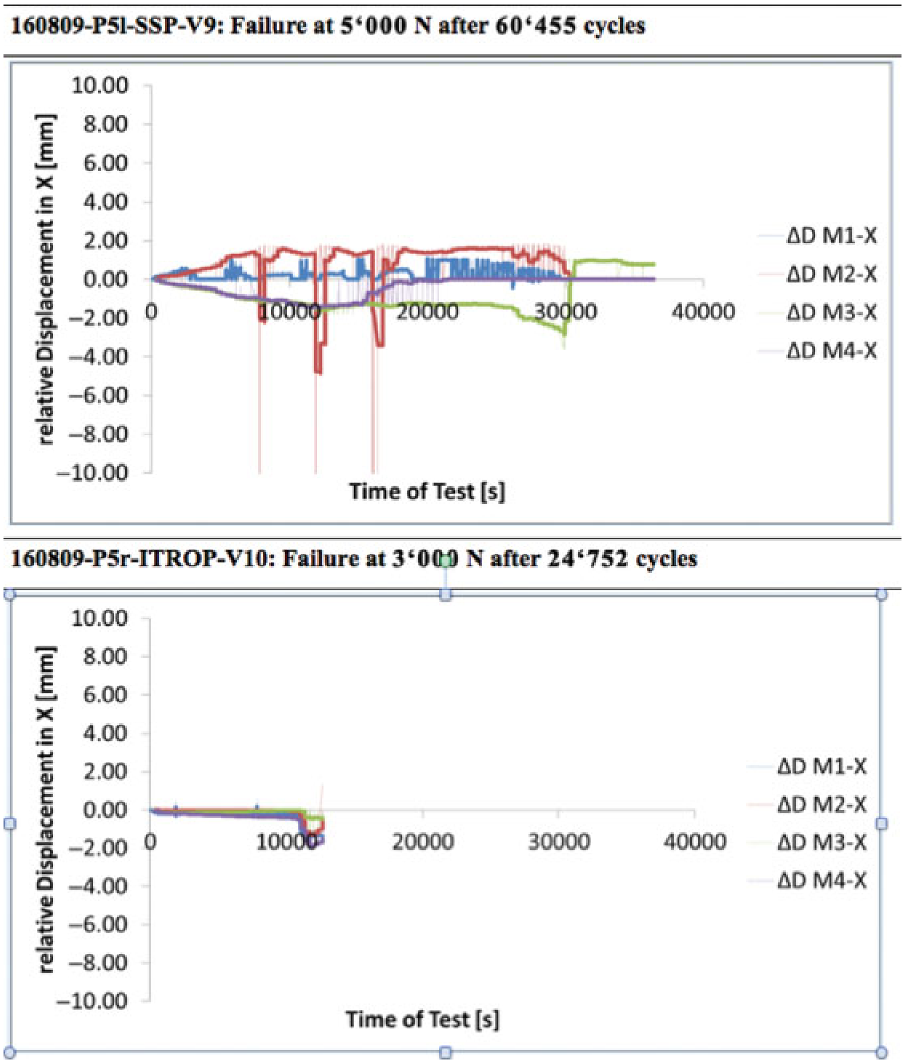


**Fig. 10** Lateromedial movement of the pin in a specimen equipped with the SSP, 6.1-mm smooth Steinmann pin (top) versus the ITROP (Imex 6.3/8.0-mm Duraface pin with thread run-out design (bottom)). Legend in plots: D-M1X/D-M2X/D-M3X/D-M4X: relative displacement of the corresponding markers no.1/2/3/4 in X direction.

tested more critically. For the IPPP, the results of the wearing out were not significantly different compared with the ITROP. For the SSP, the main reason for wearing out is thought to be the absence of threads and the concomitant increased extent of lateromedial displacement and pin loosening as discussed above. The explanation for the increased wearing out of the bones equipped with SPPP is unclear as the pin design is very similar to that of the IPPP. In light of the relevance of pin hole-associated bone fractures,[6] this cortical wear-out might be clinically relevant.

Furthermore, the diameter of the pin is an important biomechanical factor because it is a main determinant of the area moment of inertia, and thus bending stiffness. The pin diameters ranged from 6.1 to 6.3 mm; the ITROP even had a diameter of 8 mm on the thread run-out side of the pin. Since the pin stiffness increases by the fourth power of the radius increment,[12] it is evident that these variations have a large impact on the breaking strength of the pin. Obviously, the different performance of the pins tested in this study cannot be attributed to variations in pin diameter, since the pin with the smallest diameter had the highest resistance against cyclic failure.

We could not show any significant differences in frequency of pin breakage at the medial compared with the lateral aspect for the ITROP when sites of pin breakage were evaluated after biomechanical testing. Interestingly, observation with the camera during biomechanical testing revealed that the location of primary pin breakage was mostly at the medial side. This is remarkable as the medial side with the T thread run-out design has a diameter of 8 mm compared with the 6.3 mm diameter with regular positive threads on the lateral side. A possible explanation may be a combination of the following two mechanisms: first, the thicker side may have been exposed to a higher load compared with the thinner side due to the asymmetric stiffness distribution causing the thicker side to take more of the total load. Second, the crack initiation may have been favoured on that side due to a more dominant weakening/stress concentration because of the nature of the design. It was noticed that the grooves of the threads in that region caused a reduction in the large pin diameter of 8 mm (i.e. typical for a negative profile pin). On the contrary, the beginning of the threaded part at the opposite side with the smaller pin diameter represented an increase in the total cross-sectional area (i.e. typical for a positive-profile pin). Changes in pin diameter are expected to result in different local stiffness properties of the pin. This might result in local stress concentrations that could outweigh increases in pin diameter.

Limitations of this biomechanical study include unintended variations in the test set-up, such as slight differences in pin position between specimens. Theoretically, different bone diameters could also have an influence. However, there was neither a significant difference of the bone diameters between the groups nor a correlation between bone diameter and cycle numbers to failure. Although the simplified test set-up proved to be a valid model, the differences to the clinical situation are an inherent limitation. For instance, it is unclear if the lateromedial displacement of the pins in relation to the bone with its consequences on stress distribution also occurs in a real transfixation cast construct. Furthermore, in the clinical situations, more than one pin is inserted which leads to a different biomechanical situation and load distribution between the pins. For this study, we only used one pin to limit variables that would affect the outcome and are difficult to control. The use of cadaveric limbs is closer to the clinical situation than the use of artificial bones, but the effects of all biological processes such as bone response, osteointegration and local infection are neglected. Furthermore, the test set-up does not allow the evaluation of the different characteristics of a specific pin such as material properties, diameter and design on its overall mechanical performance. Finally, the material properties of the different pin types used were not examined any further.

In conclusion, the hypothesis that the new ITROP is biomechanically superior to the SPPP, IPPP and the traditional SSP under cyclic loading conditions relevant for equine transfixation pin casting patients was not confirmed in the cyclic testing model applied.

The SSP had a significantly higher number of loading cycles to failure compared with all other pin types, even though this pin was associated with more lateromedial displacement and cortical wear-out. Our results indicate that the focus for selection of the pin type for transfixation pin casting should not only be on the fixation of the pin in the bone and thus the resistance to axial extraction and pin loosening, but it should also consider the resistance to bending stress under cyclic loading.

The limitations of this biomechanical study using a simplified test model do not allow a direct advice for the clinical use of the different pin types.

### Author Contribution

Sebastian Valet and Jan M. Kümmerle contributed to conception of study, study design, acquisition of data and data analysis and interpretation. Sara A. Keller contributed to study design, acquisition of data and data analysis and interpretation. Ann Martens, Bernhard Weisse, and Anton E. Fürst contributed to conception of study, study design, and data analysis and interpretation. All authors drafted, revised and approved the submitted manuscript.

### Funding

None.

### Conflict of Interest

None declared.

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